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Magnetic-Field-Induced Metallic Phase at Low Temperature in Two-Dimensional Superconductors

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Abstract

We measure the resistance $R(T)$ at low temperature T in various fields B for an amorphous (a -)Mo_xGe_{1-x} thin film with weak disorder (i.e., small normal-state resistance R_n) and weak pinning. We confirm the presence of the intervening metallic phase between superconducting and insulating phases, consistent with earlier work on the a -Mo_xGe_{1-x} thin film with stronger disorder. The result is in contrast to what has been observed for the a -Mo_xSi_{1-x} thin films with stronger pinning, in which the B -driven superconductor-insulator transition is clearly visible. We also find that for the a -Mo_xGe_{1-x} thin films the reduced crossover temperature, below which the activated behavior of $R(T)$ in B changes to the metallic behavior, and field region of the intervening metallic phase are significantly suppressed for the less disordered film. We interpret the results in terms of decreased quantum fluctuation effects due to reduced R_n .

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1. Introduction

In uniformly disordered two-dimensional (2D) superconductors, such as amorphous thin films, a transition from superconducting to insulating states takes place either by increasing the magnetic field B or disorder (i.e., the resistance in the normal state R_n). This phenomenon, called a superconductor-insulator transition (SIT), has been studied actively over more than two decades in a variety of thin-film superconductors [1-19]. In most 2D superconductors mixed state transport properties or vortex states in the field-temperature (B - T) plane are described by the vortex-glass (VG) theory for 2D [20,21]. Our recent experiments [22] using a mode-locking technique have revealed the absence of the moving lattice state in (10 nm-thick) quasi-2D films of amorphous (a -)Mo_xGe_{1-x}, leading to a conclusion that the static vortex solid state is VG rather than the vortex lattice. The pinning strength of the a -Mo_xGe_{1-x} films is relatively weak and in the case of the thick (3D) a -Mo_xGe_{1-x} films, clear evidence of the ordered or weakly disordered lattice phase is actually observed over the broad B - T regime just below the VG phase [23]. Thus, the results obtained for the quasi-2D a -Mo_xGe_{1-x} films [22] suggest that for the thin films the vortex lattice is unstable against small pinning and the disordered VG is more favorable.

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The VG theory predicts that the VG transition in 2D is a quantum phase transition driven by B at $T=0$ from the 2D VG phase to the quantum-vortex-liquid (QVL) phase. According to the dirty-boson model [20,21], the 2D VG transition corresponds to the field-driven superconductor-insulator transition (FSIT) that occurs at the critical sheet resistance R_c close to the quantum resistance for Cooper pairs ($R_q = h/4e^2 \approx 6.45 \text{ k}\Omega$). Until now, we have provided evidence of FSIT in thin (4 or 6 nm) $a\text{-Mo}_x\text{Si}_{1-x}$ films with a pinning strength stronger than that for the $a\text{-Mo}_x\text{Ge}_{1-x}$ films based on the resistance R at low T in various B [3,4,7,8]. $R(T)$ in B below a critical field B_c of the FSIT follows the activated functional form down to the lowest T measured ($<0.1 \text{ K}$). Here, B_c and R_c [$\equiv R(T \rightarrow 0, B_c)$] are defined as a crossing point of the isothermal $R(B)$ lines in the low- T region. The experimentally extracted values of R_c are close to R_n , which are substantially smaller than R_q [3,4,7,8,24].

Meantime, in some amorphous thin (2D) films, such as $a\text{-Mo}_x\text{Ge}_{1-x}$ films [25], the existence of the intervening *metallic* phase between the superconducting and insulating phases has been reported based on the observation of a finite B regime where $R(T)$ ($<R_n$) is almost T independent near $T=0$ [25-27]. Several pictures have been proposed to explain the 2D metal phase [28,29]. Among them, there is an interesting picture, showing that a variety of materials can be collapsed onto a single phase diagram [18]. The data from different materials have been shown to collapse on two branches; one with weak disorder (small R_n) characterized by an intervening metallic phase, and the other with strong disorder (large R_n) characterized by FSIT with R_c close to R_q . The $a\text{-Mo}_x\text{Ge}_{1-x}$ thin films are located on the former branch and exhibit a metal-insulator transition. For our $a\text{-Mo}_x\text{Si}_{1-x}$ films mentioned above, disorder (R_n) is as small as that for the $a\text{-Mo}_x\text{Ge}_{1-x}$ films, but the intervening metallic phase is not present [3,4,7,8]. So, it is important to clarify what makes the difference between the low- T transport properties in the similar amorphous thin films whose degree of disorder (R_n) and superconducting properties are close to each other.

In this work, we conduct measurements of $R(T)$ at low T in various B for a thin $a\text{-Mo}_x\text{Ge}_{1-x}$ film with weak disorder. The first purpose of this work is to confirm the presence of the metallic phase in our $a\text{-Mo}_x\text{Ge}_{1-x}$ system. The second one is to clarify the effects of disorder (R_n) on transport and vortex properties at low T by examining the film with R_n much smaller than that for the film reported previously [25]. We find that the intervening metallic phase is also present in our $a\text{-Mo}_x\text{Ge}_{1-x}$ film, in contrast to the results of thin $a\text{-Mo}_x\text{Si}_{1-x}$ films. We also find from comparative plots of $\log(R/R_n)$ in different B against $(T/T_c)^{-1}$ for the two $a\text{-Mo}_x\text{Ge}_{1-x}$ films that the reduced crossover temperature (T_{cr}/T_c), below which the activated behavior changes to the metallic behavior, for our $a\text{-Mo}_x\text{Ge}_{1-x}$ film is significantly suppressed to lower T/T_c , where T_c is a transition temperature of each film. We interpret the result, together with the suppression of the intervening metallic phase along the B axis, in terms of decreased quantum fluctuation effects due to reduced R_n .

2. Experimental

We prepared the $a\text{-Mo}_x\text{Ge}_{1-x}$ film with thicknesses of 6 nm by rf sputtering on a silicon substrate mounted on a water cooled rotating copper stage [22,23]. The sheet resistance in the normal state at 10 K is $R_n = 0.3 \text{ k}\Omega$. The mean-field transition [$R(T_{c0}) = 0.95R_n$] and zero-resistivity temperatures [$R(T_c) = 10^{-3}R_n$] are $T_{c0} = 3.3 \text{ K}$ and $T_c = 2.6 \text{ K}$, respectively. The superconducting coherence length ξ estimated from the upper characteristic field where $R(B) = 0.99R_n$ at $T \approx 0$ is around 20 nm, which is larger than the film thickness of 6 nm. Thus, the dimensionality with respect to ξ is considered to be 2D. The weaker pinning strength for $a\text{-Mo}_x\text{Ge}_{1-x}$ than that for $a\text{-Mo}_x\text{Si}_{1-x}$ is confirmed from the facts that (i) for the thick films of $a\text{-Mo}_x\text{Ge}_{1-x}$ the depinning current density J_c , as estimated from current-voltage characteristics [23], is more than one order of magnitude smaller than that for the $a\text{-Mo}_x\text{Si}_{1-x}$ film [30] and that (ii) $J_c(B)$ for the thick $a\text{-Mo}_x\text{Ge}_{1-x}$ films exhibit a clear peak effect at a certain field B_p just prior to melting, indicative of an order-disorder transition of vortex matter at B_p [23]. By contrast, the peak effect is never visible for the $a\text{-Mo}_x\text{Si}_{1-x}$ films [30].

The linear resistance R was measured using a four-terminal dc and low frequency (19 Hz) locking methods, where we always checked the ohmic response. All the data presented in this paper were taken in our ^3He - ^4He dilution refrigerator. The magnetic field B was applied perpendicular to the surface of the film.

3. Results and Discussion

First, we show in Fig. 1(a) the resistance ($\log R$) vs T plots in different B obtained previously for the 6 nm thick $a\text{-Mo}_x\text{Si}_{1-x}$ film with $T_{c0} = 2.0 \text{ K}$, $T_c = 1.4 \text{ K}$, and $R_n = 0.7 \text{ k}\Omega$ [31]. The high- R part is enlarged and shown in the inset. We find that the FSIT takes place between 6 and 7 T ($=B_c$). It is also found from the Arrhenius plot (not shown here) that below B_c , $R(T)$ follows the activated functional form down to the lowest T ($\approx 0.06 \text{ K}$) measured. These results clearly show the absence of the intervening metallic phase at $T=0$.

Figure 1 (b) depicts the Arrhenius plots of $R(T)$ (solid circles) in different B for the 6 nm thick $a\text{-Mo}_x\text{Ge}_{1-x}$ film. Here, R is normalized by R_n and a horizontal dotted line at the lower part of the figure represents the experimental resolution. In $B < 3.5 \text{ T}$, $R(T)$ exhibits the superconducting behavior with R falling to zero at nonzero T , while in $B = 11 \text{ T}$, $dR(T)/dT$ takes negative values, indicative of the insulating behavior. In B between 4 and 5 T, the T independent (or T insensitive) $R(T)$ that spans the broad range [$R/R_n = 2 \times 10^{-3} - 3 \times 10^{-1}$] is clearly observed at low T , indicating the

presence of the intervening metallic phase. The data points for the 3 nm thick $a\text{-Mo}_x\text{Ge}_{1-x}$ film with $R_n=1.4\text{ k}\Omega$ and $T_c\approx 0.5\text{ K}$ [25], which were collected from Fig. 1 in Ref. 25, are plotted with open squares for comparison on the same figure. The solid and dotted arrows representatively mark the crossover temperature T_{cr} below which the activated behavior changes to the T independent metallic behavior for the 6 nm and 3 nm thick $a\text{-Mo}_x\text{Ge}_{1-x}$ films, respectively. It may be interesting to note that although the degrees of disorder R_n and values of T_c between the two films are much different, the data points of R/R_n fall on roughly the same curves. At present, there is no theoretical interpretation to explain the finding. Here, we only note the well accepted fact that the characteristic temperature below which the transport and vortex properties are dominated by quantum fluctuations is better described by the reduced temperature T/T_c rather than T [32,33]. Thus, in Fig. 1(c) we plot the same data of $R(T)/R_n$ as shown in Fig. 1(b) against the inverse of the reduced temperature $(T/T_c)^{-1}=T_c/T$. It is clearly seen that for our 6 nm thick $a\text{-Mo}_x\text{Ge}_{1-x}$ film with $R_n=0.3\text{ k}\Omega$ and $T_c=2.6\text{ K}$, the reduced crossover temperature T_{cr}/T_c (indicated with a solid arrow) from the activated to metallic behavior is significantly suppressed to lower T/T_c compared to that (indicated with a dotted arrow) for the 3 nm thick $a\text{-Mo}_x\text{Ge}_{1-x}$ film [25].

In Fig. 1(d) we illustrate the phase diagram in the B - T plane for the 6 nm thick $a\text{-Mo}_x\text{Ge}_{1-x}$ film with $R_n=0.3\text{ k}\Omega$ and $T_c\approx 2.6\text{ K}$, showing the location of B_{cr} [$\equiv B(T_{cr})$] (red solid circles), B_{c0} (red open circles) where $R(B)$ falls to zero, B_{c2} (red solid squares) where $R(B)$ approaches R_n , that is, any sign of superconductivity disappears, and the critical field

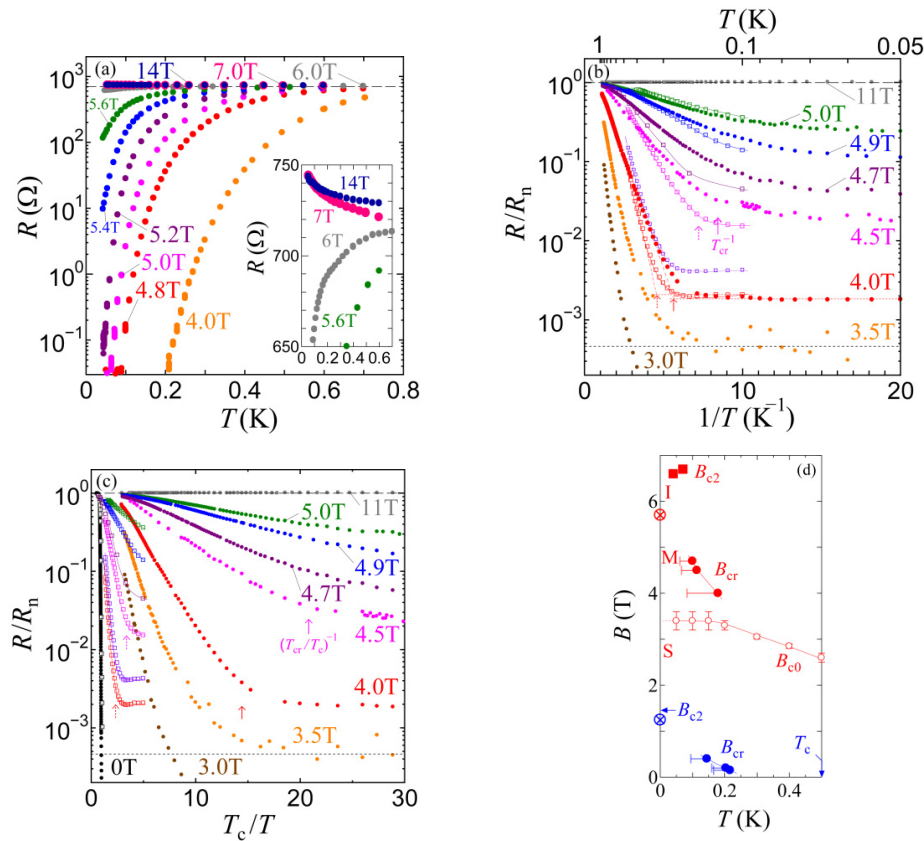


Fig. 1. (a) $\log R$ vs T plots in different B for the 6 nm thick $a\text{-Mo}_x\text{Si}_{1-x}$ film with $T_{c0}=2.0\text{ K}$, $T_c=1.4\text{ K}$, and $R_n=0.7\text{ k}\Omega$ [31]. Inset: The high- R part is enlarged and shown. (b) Arrhenius plots of R/R_n (solid circles) in different B for the 6 nm thick $a\text{-Mo}_x\text{Ge}_{1-x}$ film with $R_n=0.3\text{ k}\Omega$ and $T_c=2.6\text{ K}$. A horizontal dotted line at the bottom indicates the experimental resolution. Open squares represent the data points for the 3 nm thick $a\text{-Mo}_x\text{Ge}_{1-x}$ film with $R_n=1.4\text{ k}\Omega$ and $T_c\approx 0.5\text{ K}$ collected from Ref. 25. The solid and dotted arrows mark the crossover temperature, below which the activated behavior changes to the T independent metallic behavior for the 6 nm and 3 nm thick $a\text{-Mo}_x\text{Ge}_{1-x}$ films, respectively. (c) The same data as shown in (b) are plotted against $(T/T_c)^{-1}$. A horizontal dotted line represents the experimental resolution. The solid and dotted arrows indicate the reduced crossover temperature from the activated to the metallic behavior for the 6 nm and 3 nm thick $a\text{-Mo}_x\text{Ge}_{1-x}$ films, respectively. A horizontal dashed line at the upper part of each figure marks the location of R_n . Other lines are the guide for the eye. (d) B - T phase diagram for the 6 nm thick $a\text{-Mo}_x\text{Ge}_{1-x}$ film with $R_n=0.3\text{ k}\Omega$ and $T_c=2.6\text{ K}$ (red symbols) and for the 3 nm thick $a\text{-Mo}_x\text{Ge}_{1-x}$ film with $R_n=1.4\text{ k}\Omega$ and $T_c\approx 0.5\text{ K}$ [25] (blue symbols). The lines are the guide for the eye. "S", "M," and "I" denote the superconducting, intervening-metallic, and insulating phases at $T=0$, respectively, for the 6 nm thick $a\text{-Mo}_x\text{Ge}_{1-x}$ film.

B_c (a red cross circle) of the ($T=0$) metal-insulator transition where the isothermal $R(B)$ lines in the low- T region cross each other. Also shown with blue solid circles and a cross circle are B_{cr} and B_c , respectively, for the 3 nm thick a - $\text{Mo}_x\text{Ge}_{1-x}$ film with $R_n=1.4 \text{ k}\Omega$ and $T_c \approx 0.5 \text{ K}$ [25]. Compared to the 6 nm a - $\text{Mo}_x\text{Ge}_{1-x}$ film, the field region, $1-B_{c0}(T=0)/B_c$, of the intervening metallic phase seems to larger, with B_{cr} extending down to low fields ($B_{cr}/B_c \approx 0.12$), and the ($R=0$) superconducting phase (S) is not observed down to the lowest B ($=0.15 \text{ T}$) [25]. Assuming that the origin of the intervening metallic state is due to the QVL caused by strong quantum fluctuations and using the theoretical prediction that the strength of quantum fluctuations is proportional to disorder (R_n) of the films [24,32,33], the observed suppression of T_{cr}/T_c and $1-B_{c0}(0)/B_c$ (i.e., that of the metallic phase along the T and B axes, respectively) for our 6 nm a - $\text{Mo}_x\text{Ge}_{1-x}$ film may be explained in terms of the decreased quantum-fluctuation effects due to reduced R_n .

4. Summary

To summarize, we present measurements of $R(T)$ at low T down to $T/T_c=0.02$ in different B for the a - $\text{Mo}_x\text{Ge}_{1-x}$ thin film with weak disorder and pinning. We confirm the presence of the intervening metallic phase between the superconducting and insulating phases, as reported previously on the a - $\text{Mo}_x\text{Ge}_{1-x}$ thin film with stronger disorder [25]. The result is in contrast to that for the a - $\text{Mo}_x\text{Si}_{1-x}$ thin films with stronger pinning and similar R_n , where FSIT is clearly visible. We also find that for the a - $\text{Mo}_x\text{Ge}_{1-x}$ thin films the reduced crossover temperature T_{cr}/T_c , below which the activated behavior changes to the metallic behavior, is significantly suppressed from a few tens percent to the order of a percent and the (reduced-)field region $1-B_{c0}(0)/B_c$ of the intervening metallic phase is also suppressed from more than 0.9 to 0.4, as R_n is decreased from 1.4 to 0.3 $\text{k}\Omega$. We interpret the results in terms of decreased quantum fluctuations.

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